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Economics of Advanced Thin-Haul Concepts and Operations

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The thin-haul commuter concept refers to an envisioned class of four to nine passenger aircraft operating very short flights and providing scheduled and on-demand air services from smaller airports. Its objective is to enhance regional mobility reach by combining the flexibility of automobile travel with the shorter commute times associated with air travel. To achieve economic viability, the thin-haul commuter concept must provide appreciable economic advantages when compared to current commuter aircraft. This may be achieved by increasing the revenue potential through innovative pricing and scheduling, while drastically reducing operating costs, in particular, energy, maintenance, and labor costs. These ambitious objectives require the infusion of new cutting edge technologies. The use of distributed electric propulsion is investigated to reduce both energy and maintenance expenditures. New avionics systems are considered to enable simplified operations and thus to reduce both labor and training costs. The purpose of this on-going research is to assess the viability of the thin-haul aviation concept by investigating both the operational and economic impact of introducing a fleet of distributed electric propulsion aircraft into the operations of a commuter airline. This paper presents the development of an integrated economics and operations model that incorporates preliminary estimates of a distributed electric propulsion vehicle performance as well as some aspects of typical commuter operator schedules. The model helps compare advanced electric vehicles with more conventional commuters, and therefore enables a preliminary assessment of the expected cost savings.

Nomenclature

DEP Distributed Electric Propulsion
DOC Direct Operating Cost
CDF Cumulative Distribution Function

I. Introduction

There are over 19,500 airports in the United States, of which approximately 5,000 are public.[1] Within this extensive network of public airports, only approximately ten percent are part of the commercial air transportation network while the remainder are highly underutilized in comparison.[2] To understand the reasons for this underutilization requires a review of the segmentation of demand for air travel and an understanding of the types and economics of operators catering to these different market segments. Most of the demand for air transportation in the United States is highly concentrated in relatively few routes, typically connecting major hubs across the country. A few examples of these routes are depicted in the

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representation of Figure 1. These routes are usually served by large commercial airlines such as Southwest Airlines, Delta Air Lines, United Airlines, etc., using large capacity aircraft (greater than 100 passengers) to handle a large volume of passengers. Complementing these trunk routes are routes with lower demand which are traditionally served by regional airlines such as Horizon Air and Skywest Airlines which usually operate turboprops and regional jets with smaller capacity (between 35 and 70 passengers). Finally, at the opposite end of the spectrum are routes with very low demand and very short trip distances (less than 200 nmi) usually served by commuter airlines such as Cape Air, Mokulele Airlines, and Surf Air. These operators connect smaller communities within the same region with point-to-point services. Since the passenger volume is low for these routes, commuter operators usually fly small capacity aircraft such as the Cessna 402, Cessna Grand Caravan, or Pilatus PC-12.

This latter *thin-haul* market segment presents many opportunities and challenges for current and prospective operators. For example, although the demand for each individual route in a thin-haul network may be limited, the cumulative demand across all routes in a networkand particularly the latent demand that would emerge if ticket prices could be reducedis significant. This cumulative and latent demand indicates that there is a potential for significant profitability if thin-haul routes can viably be served by commercial operators. However, despite this demand and the extensive and underutilized airport infrastructure available, businesses in the thin-haul market segment have not collectively experienced high growth rates and seem often reluctant to expand their operations. The primary reason for this cautious approach is related to the high operating costs involved in catering to thin and geographically-distributed demand: whereas large scale commercial operators such as Delta Airlines incurred typical operating costs of \$0.13 per available seat-mile,[3] in 2015 dollars, commuter operators such as Cape Air incurred operating costs reaching \$0.47 per available seat mile[4] due in large part to the relative per-seat efficiency of the aircraft. These high operating costs compounded with the elasticity of the demand for air travel and the availability of alternate modes of transportation for thin-haul routes (e.g. automobiles) make it difficult for commuter airlines to operate profitably. Consequently, a paradigm shift in the design of commuter aircraft is required to enable operators to efficiently and viably grow their operations in this segment of the market.

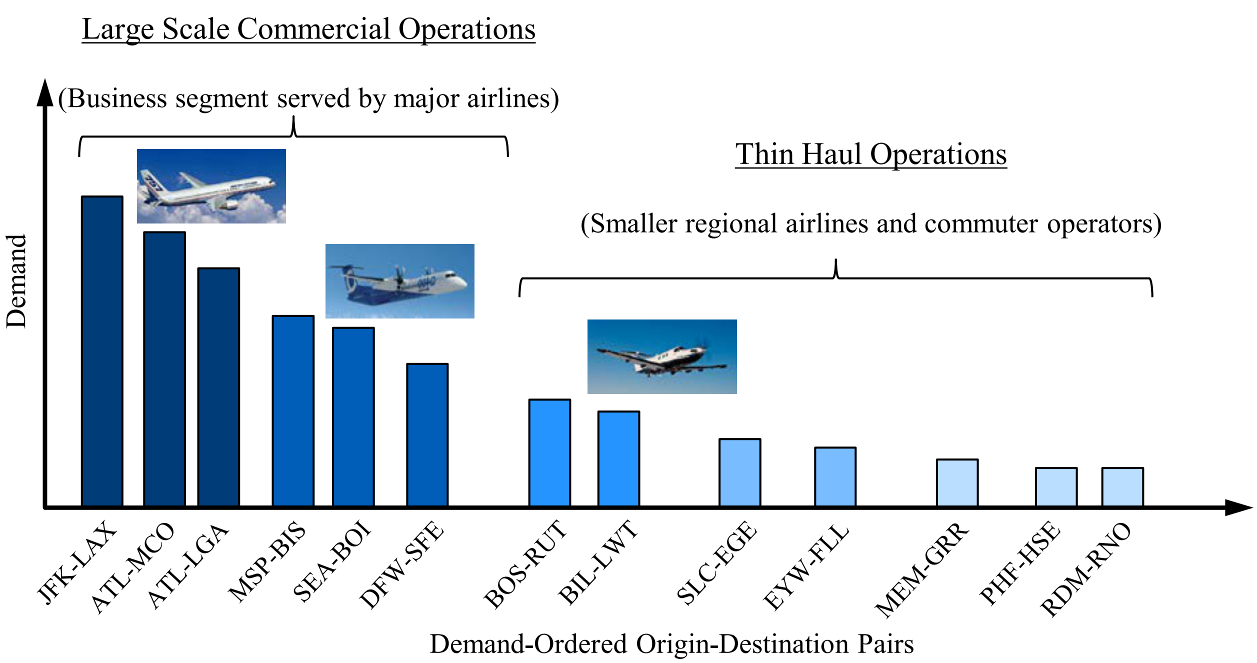

Figure 1. Demand distribution for air travel

II. Motivation and Project Statement

The large, yet untapped, demand as well as the limited growth of current commuter air operations have motivated NASA to investigate opportunities to reenergize the thin-haul aviation market.[5] The objective is to study the impact of a new class of small ultra-efficient aircraft and their associated concepts of operations which would leverage recent technological opportunities.[5] The vision is a viable thin-haul air travel solution with drastically lower operating costs. This would allow commuter airlines to grow their operations, to address the latent demand in existing thin-haul networks, to develop new routes, and ultimately to provide ubiquitous quasi-on-demand regional air transportation. The greater availability and lower cost of thin-haul commuter flights would yield door-to-door multi-modal regional travel solutions that combine the flexibility of the automobile with the speed of air travel. This revolution in regional air travel would fundamentally alter our understanding of transportation by bringing aviation into our daily lives, increasing regional reach, and reducing commuting time.[5,6]

Joby Aviation, in collaboration with NASA, is developing advanced aircraft concepts for the thin-haul market segment. These concepts benefit from the convergence of many emerging airframe, propulsion, and avionics technologies. A key enabler is Distributed Electric Propulsion (DEP)[7] which takes advantage of the scale-free nature of electric motors to achieve propulsion from a set of smaller electric motors. Each motor drives its own propeller and this can be achieved without a significant loss of efficiency or specific power.[7] The combination of motors and propellers is distributed in advantageous locations on the airframe to achieve reduced drag and/or improved propulsive efficiency. One promising configuration distributes multiple propellers along the wing leading edge. During operations, these individual propellers blow high velocity air over the wing surface, thus increasing lift at low speeds, in particular during take-off and landing. During cruise, high lift generation is no longer required, and most of the propellers are folded to minimize drag. In addition to the benefits of electric propulsion (lower energy cost, lower maintenance, reduced emissions, etc.), the high lift potential of this type of propulsion system at low speeds allows a significant reduction in wing area for a given vehicle size, reducing drag during cruise despite the added excrescence drag of the motor pods. A smaller wing area also provides higher wing loading which reduces sensitivity to gusts and therefore improves ride quality, a consideration often mentioned by passengers of current small commuter aircraft. Through concepts developed in the NASAs Leading Edge Asynchronous Propeller Technology (LEAPTech) program, Stoll et al.[7] demonstrate that a DEP architecture of this type can generate a $C_{L_{\max}}$ exceeding 5.2 at low speeds thanks to the blowing effect of the multiple propellers, while achieving a lift-to-drag ratio in excess of 20 in cruise with folded propellers. These numerical results were validated experimentally with the NASA Hybrid Electric Integrated Testbed (HEIST).[8]

Using electric power may also result in a significant reduction in energy need and energy-related expenditures. Compared to internal combustion engines with thermal efficiencies on the order of 25% to 28%, a battery-electric architecture has the potential to reach a much higher energy transfer efficiency as the fraction of the energy from the battery that is available for propulsion depends primarily on the efficiency of the electric motor and inverter. Based on currently available technologies, motor efficiencies of 98% and inverter efficiencies of 97% are readily achievable over relatively wide operating conditions. This results in an overall transfer efficiency greater than 95%.[9] To enable swift adoption by thin-haul operators, new DEP aircraft must provide appreciable economic benefits over current commuter aircraft and must effectively address the high operating costs that are currently hindering a thriving commuter market segment. The objective of this study is to assess the economic viability of aircraft concepts currently being investigated by NASA and Joby Aviation through a detailed investigation of current commuter operations, distributed electric propulsion technology, and DEP aircraft performance. In this context, the target set forth by NASA of a 30% reduction in Direct Operating Costs[10] is retained as providing enough incentive for commuter operators to transition from a conventional aircraft to a DEP aircraft. In summary, the purpose of this research is to answer the following questions:

- Is current distributed electric propulsion technology sufficient to achieve the target reduction in operating costs for thin-haul commuter aircraft?
- What levels of fuel and electricity prices would provide adequate incentives for operators to transition to distributed electric propulsion aircraft?
- Can distributed electric propulsion aircraft be incorporated into typical commuter operations without negatively impacting the turn-around time between flights and the yearly aircraft utilization?

III. Methodology

The high operating costs of commuter operations have been previously alluded to as preventing thriving thin-haul operations. In this section, a typical breakdown of the direct operating costs of a commuter operator is presented and the different sources of operating costs are reviewed. Next, the approach undertaken for modeling the different parts of the operating costs is presented with emphasis on areas likely to be impacted by the adoption of an electric propulsion architecture.

The typical breakdown of direct operating costs for a commuter aircraft operating under Part 135 is presented in Figure 2. Maintenance and reserves represent the largest share at over 40% of the direct operating costs. This is very different from Part 121 airlines but this is typical for operators flying ageing piston aircraft requiring frequent maintenance. Indeed, with engine overhauls typically scheduled between 1,500 and 2,000 hours, both engines of a twin engined aircraft need to be completely removed and overhauled every year and a half given typical commuter aircraft utilization. The frequency of engine overhauls could be improved by transitioning to aircraft with modern electric motors having few moving parts and therefore reduced maintenance needs.

The next largest source of expenditures is fuel. Fuel expenditures, in addition to being significant, are subject to considerable volatiliy owing to the complex energy market. This energy cost element could be beneficially impacted by adopting aircraft featuring an electric propulsion, considering the reduced cost of grid-derived electrical energy compared to aviation gasoline.

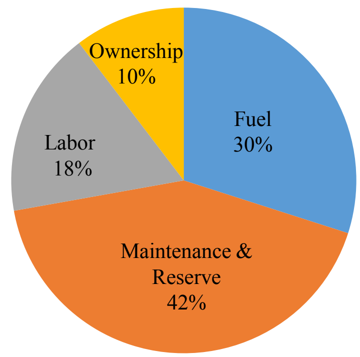

Figure 2. Direct Operating Cost breakdown from 2015 EAS proposal of Cape Air[4] [St-Louis (STL) to Cape Girardeau (CGI)]

Next are labor costs which are relatively low compared to major airlines. Lower labor costs for commuter and regional airlines result from the seniority structure of airline crew pay and the practice of hiring pilots at the beginning of their careers for commuter and regional aviation. Labor costs could be further reduced by transitioning to aircraft with increased degrees of automation that might, with changes in pilot certification regulations, result in a reduction in the initial and recurrent training costs for flight crews.

Ownership costs are the smallest cost element in the direct operating cost. Unless significant gains in aircraft utilization are achieved, ownership costs may be negatively impacted when transitioning to new aircraft employing advanced technologies such as distributed electric propulsion and advanced automated systems as acquisition prices of state-of-the-art vehicles will come at a premium.

Furthermore, when transitioning to a new distributed electric propulsion architecture, additional costs for battery reserves need to be considered since batteries are expensive and have a limited operating life, usually expressed in terms of charge and discharge cycles.

Although many life-cycle cost models such as the Aircraft Life Cycle Cost Analysis (ALCCA)[11] and the Integrated Cost And Revenue Estimator (ICARE)[12,13] exist, they usually lack the flexibility to incorporate new unconventional concepts. Hence, a new economics model capable of determining the individual components of the direct operating costs is required. The development and the key assumptions underlying the model are discussed in greater details in the following subsections.

III.A. Energy Cost Model

Fuel is one of the most significant and volatile sources of expenditure for commuter operators. By shifting from a conventional aircraft running on aviation fuel to an electric vehicle, considerable savings in energy cost may be achieved. Since this has potentially significant implications, a careful consideration of the various elements affecting the cost of electricity is warranted.

III.A.1. Electric Energy Pricing

Research on electricity rates indicates that the cost of electricity not only varies from city-to-city and from provider-to-provider, but it is also highly dependent on how the electric energy is drawn from the grid. In most cases, the electricity bill can be subdivided into two parts, the *Supply* side and the *Delivery* side as indicated in Figure 3. The *Supply* side corresponds to the cost of producing electric energy and electric power, while the *Delivery* side corresponds to the cost of transporting this energy from its place of production to the end-consumer. Moreover, each of these two elements is further subdivided into at least two subparts. One subpart is related to the amount of energy used by the end-consumer and therefore the amount of energy that needs to be produced (cost of producing electricity from coal, fuel, uranium, sun, wind). The other subpart is related to the peak power potentially required by the end-consumer, which basically dictates the infrastructure needed to meet the end-consumer electricity demand (peaker gas turbine). In addition, extra charges are sometimes added on the *Delivery* side such as monthly user charges (to administer the end-consumer account) and grid access charges (to connect isolated places to the grid).

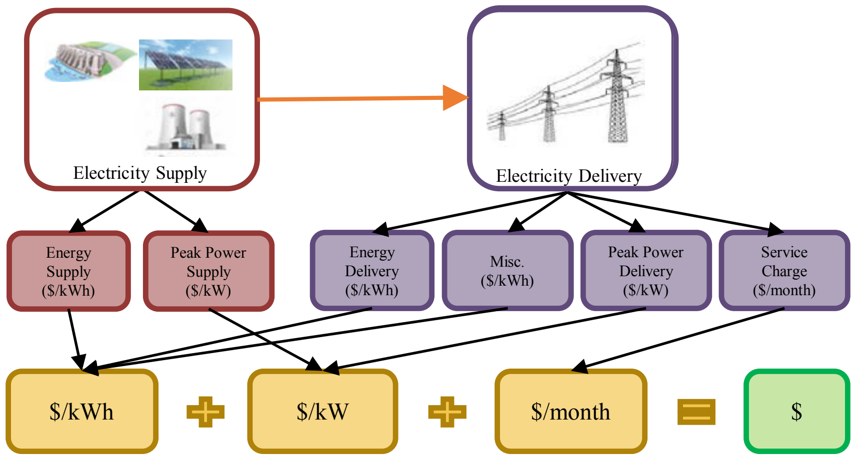

Figure 3. Electricity rate determination flowchart

The electricity rate schedules of utility providers detail how the final cost is computed and preliminary investigations indicate that electricity rates are extremely sensitive to the peak-power demand. The cheaper electricity rates are achieved by having a continuous and flat energy draw from the grid. This may prove problematic for commuter operators trying to quickly recharge batteries on-demand whenever an aircraft lands at an airport. Determining the electricity rate applicable to a thin-haul operator at each and every airport within the network is therefore a complicated process:

- The energy consumption at each airport in the network needs to be determined and it differs from airport to airport based on the frequency of flights and the need to recharge batteries
- The peak power at each airport in the network needs to be determined and it depends on the number of aircraft batteries that need to be recharged simultaneously. Incidentally, determining this peak power is equivalent to determining the number of charging stations needed at each airport. The characteristics of the charging stations (regular chargers or superchargers with higher power draw) are determined by the turn-around-time of aircraft at the airport and the energy requirements for flights departing from that airport.
- Once both the electric energy need and the peak-power demand are estimated, the appropriate electricity rate schedule at each airport can be determined. Nevertheless, each airport in the network may be serviced by a different utility provider which compounds the complexity of the problem as different electric rate schedules need to be retrieved and analyzed to determine which rate is applicable.

Ideally, and to minimize the cost of electricity at a given airport, the peak power drawn from the grid at any time should be minimized. As mentioned earlier, one way to approach this idealized power draw is to ensure that a fixed (and constant) number of batteries are continuously charged during the day. This is however impractical for operators due to the considerable scheduling challenges involved. A less intrusive approach, adding nonetheless a layer of logistical complexity, is to use spare batteries to draw constantly from the grid at relatively low powers throughout the day and to switch batteries as aircraft land. Finally, another solution to handle peaking loads resulting from the need to recharge batteries of intermittently arriving aircraft would be to use fuel-based ground power units at airports.

III.A.2. Power Requirements and Energy Needs

Power requirements for takeoff, climb, and cruise are direct consequences of the vehicle design. The total amount of energy required to complete a flight mission is calculated as the sum of the power requirements for each phase of the flight multiplied by the time required to complete the corresponding phase of flight. Losses are accounted for using electric component efficiencies. For instance, electric motor and generator efficiencies of 98% and inverter efficiency of 97%[9] are assumed in order to determine the total energy transferred from the battery to the propellers. In addition, the efficiency of the battery charger on the ground needs to be accounted for owing to the heat losses experienced during fast charging of electric batteries. An efficiency of 90% is assumed for the battery charger.

An additional factor to be considered with respect to the energy transfer from the battery to the propeller is the battery depth of discharge, i.e., the percentage of the battery capacity that is discharged during operations. Indeed, deep discharges are known to significantly reduce battery life[14] and for this reason the depth of discharge is limited to 80% of the battery capacity in order to maintain a reasonable battery life. Batteries are thus recharged such that the battery charge at completion of each flight is at least 20% of the battery capacity. Figure 4 summarizes the determination of the energy need and electricity cost based on the different factors described so far.

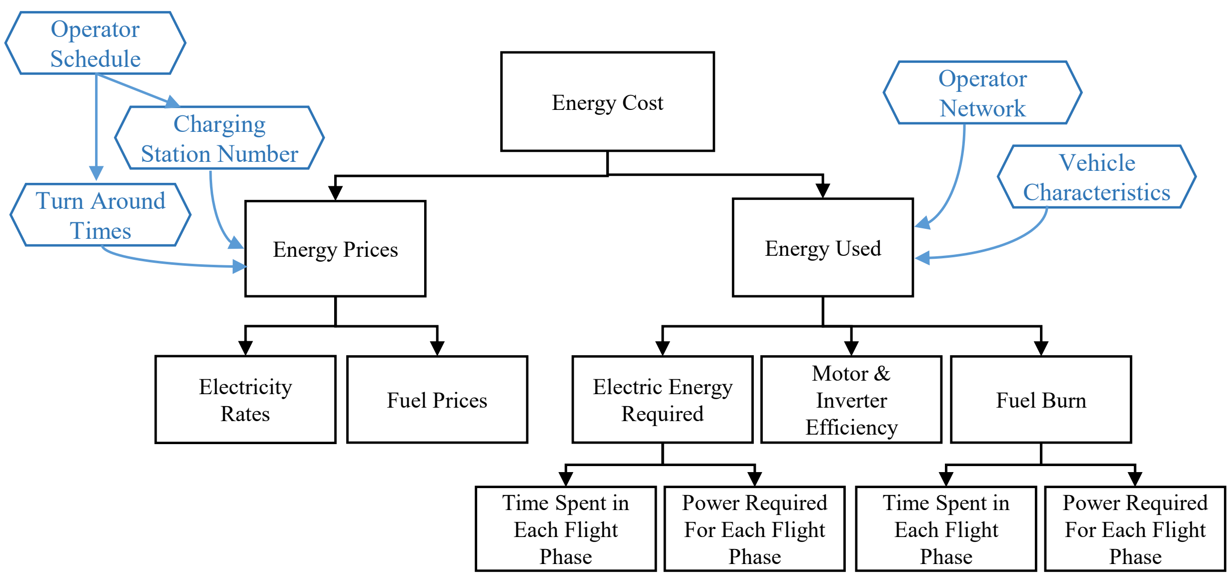

Figure 4. Energy cost model description

III.B. Maintenance Cost Model

Developing an accurate maintenance cost model is a difficult task owing to the difficulty in forecasting expected maintenance expenditures for future revolutionary aircraft concepts based on new technologies. A credible model must be able to estimate the differences in terms of maintenance costs between a conventional thin-haul commuter aircraft and a new aircraft featuring a distributed electric propulsion system. Two approaches have been identified as suitable to generate an appropriate maintenance cost model. The first consists in developing estimates based on bottom up aggregation of maintenance costs of individual aircraft components, while the second involves top down semi-empirical relationships found in the literature based on aggregate aircraft characteristics. The second approach is chosen owing to the lack of public domain data regarding failure rates and deterioration of individual aircraft components and information about specific cost drivers of electric propulsion maintenance (routine maintenance for electric motors, inverters, and batteries).

Consequently, the overall semi-empirical approach of Roskam[15] is retained. It is articulated around the computation of six sources of maintenance expenditures: material expenditures for the airframe, material expenditures for the powerplant, labor expenditures to maintain the airframe, labor expenditures to maintain the powerplant, maintenance reserves for the overhaul of the powerplant (depreciation of the engine(s) in between successive overhauls), and finally, the applied maintenance burden which accounts for the overheads associated with maintenance events. Besides some basic aircraft characteristics (airframe empty weight, engine weight, number of engine(s), airframe material, typical block speed, engine overhaul cost), the main input for this model is the labor rate which, following the statistics compiled by the Bureau of Labor Statistics,[16] is assumed to be $28/hour for airframe and power plant mechanics. An overview of the model is presented in Figure 5.

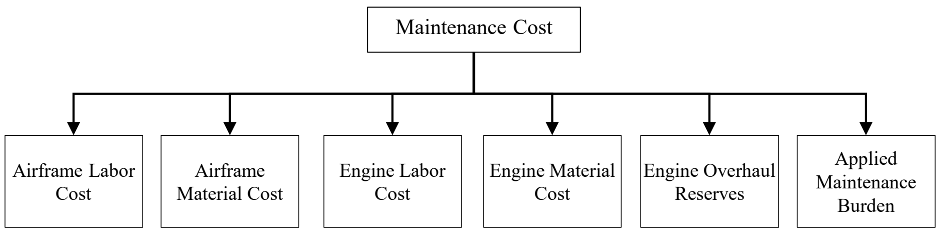

Figure 5. Maintenance cost model description

For a new concept featuring a composite airframe and a distributed electric propulsion system, adjustment k-factors are used in order to account for the impact of these new technologies on maintenance expenditures and the literature is used to calibrate them. According to Boeing,[17] a composite airframe reduces by 35% the required number of maintenance man-hours owing to the lack of corrosion and the resulting need for fewer scheduled inspections. Another adjustment factor is used to account for the reduced maintenance of electric motors: data collected from the automotive industry indicates that hybrid-electric and electric vehicles experience a reduction of 20% of the engine labor and engine material costs due to the reduction in the number of moving parts and the elimination of consumable components.[18] Finally, the engine overhaul reserves are completely neglected owing to the fact that electric motors will not be overhauled during the operating life of the aircraft. Indeed, the expected life of electric motors is longer than the operating life of aircraft and therefore no reserve needs to be set aside for their replacement.

III.C. Labor Cost Model

The labor cost is another significant source of expenditures for thin-haul operators as reflected by the Essential Air Service (EAS) application data presented in Figure 2. Labor cost includes expenses due to crew wages and benefits, crew training, and overhead.[19] To enable a quantification of the potential reduction in labor costs resulting from increased cockpit automation and reduced flight crew training, a bottom-up approach is developed and the different components of the labor cost are individually modeled and aggregated together as indicated in Figure 6.

The crew productivity and the number of flight crews required to operate the schedule are first investigated. The flight crew productivity is assessed by computing the minimum number of crews needed to fly the schedule given the maximum annual flight-hours, the maximum monthly flight hours, the maximum monthly duty-time, the maximum weekly duty time, the maximum daily duty time, and the minimum weekly rest period set forth in FAA regulations.[20] Some of these regulations, like maximum daily duty time, depend on the number of flight segments flown by crews as well as the time at which crews reported to work. This preliminary estimate of flight crew productivity is adjusted next to account for idiosyncrasies of Part 135 commuter operators such as vacation time and the typical structure of flight-crew rosters. This yields a refined estimate of the number of flight crews required, as well as their annual number of flight hours and duty time. Subsequently, these estimates are used to assess the labor expenditures using typical commuter and regional industry pay scales and typical per diem.[21] Overhead costs are estimated next as a fraction of the flight crew salaries to account for additional expenditures related to retirement contributions and other benefits offered to flight crews.

Next, training expenditures are estimated using Part 135 regulations and standard industry practices as described by Wijayawardana.[22] Training is categorized into Initial New Hire Training commonly referred to as basic indoctrination, Transition Training when crew are switching from aircraft to aircraft, Upgrade Training when crews switch from second-in-command to pilot-in command positions, Difference Training used to highlight the small differences between variants of the same aircraft, Recurrent Training to maintain crew skills and currency, and finally Requalification Training for crews whose currency may have lapsed. For the purpose of this research, a fleet of a single type of aircraft is retained and therefore only the Initial New Hire Training, Upgrade Training, and Recurrent Training are investigated. The cost for Initial New Hire Training is assumed to be amortized over the first five years of employment during which a new hire is assumed to work as second-in command. The cost for Upgrade Training is assumed to be amortized over the following five years during which the crew is upgraded to a pilot-in command position. After this, the model assumes that the crew is moving on to a larger operator featuring larger aircraft and probably more attractive pay scales.

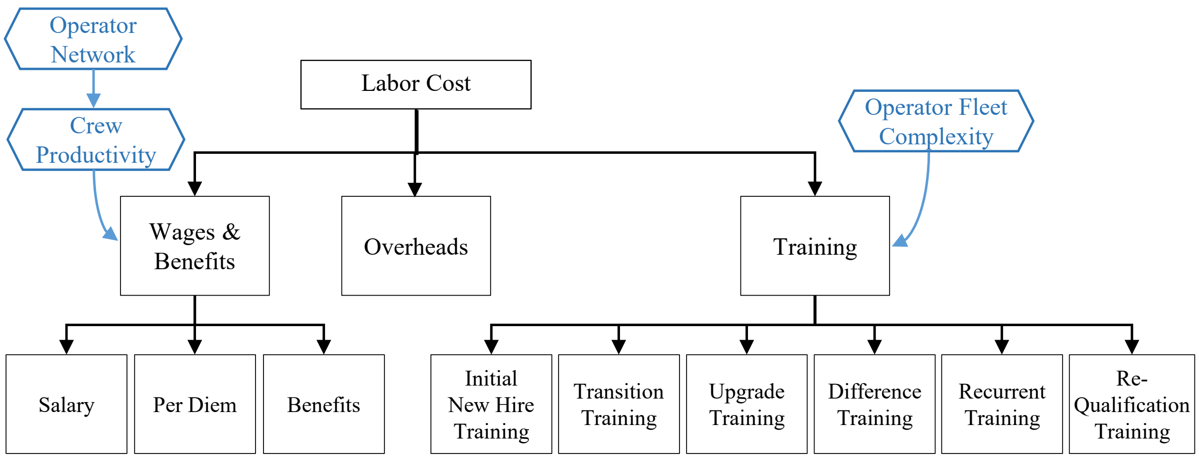

Figure 6. Labor cost model description

Assuming the pay scale for conventional and distributed electric propulsion concepts are similar, the same labor cost model can be used to study both conventional and electric vehicles. Even though no major difference in labor costs is therefore expected, incremental reductions are observed for three reasons:

- First, the number of flight crews required to fly the operator schedule may differ for each aircraft concept. Even though the DEP concept and many typical Part 135 commuter aircraft are certified for single-pilot operations, some operators prefer to have two pilots for increased safety, while other operators need two pilots for specific flights in order to fulfill the Department of Transportation requirement for the Essential Air Service program. Advances in avionics leading to more automation and simplified vehicle operations may nonetheless help operators (and regulators) transition to single-pilot operations in the future, thereby decreasing significantly labor costs.
- Second, simplified vehicle operations will likely reduce the amount of initial training needed for newly-hired flight crews and will concurrently reduce recurrent training needed for seasoned flight crews. This will likely result in decreased labor costs.
- Third, the increased cruising speed of the distributed electric propulsion concept allows flight crews to complete more missions during a single day. Therefore, fewer crews are required in order to fly a specific operator schedule.

III.D. Battery Reserve Model

The battery reserve is a component of the direct operating costs that is applicable only to battery-electric vehicles. It refers to the cost of replacing the battery pack at the end of its useful life. For this analysis, the battery reserve is computed using high level metrics, namely, the battery life expressed in terms of cycles and the battery capacity specific cost expressed in $/kWh. The battery life represents the expected number of charging and discharging cycles that a battery can sustain before losing twenty percent of its initial rated capacity. Modern lithium-ion battery have typical lives between 1,000 to 2,000 cycles[23] depending mostly on the average depth-of-discharge during operations. The battery capacity specific cost represents the cost of the battery with respect to its energy capacity. Current state-of-the-art batteries used in the automotive industry are priced at $250/kWh.[24] However, significant research effort is presently being expended in the automotive industry to produce better and cheaper batteries, and the capacity specific cost of lithium-ion batteries is expected to fall to the $100/kWh to $150/kWh price range by 2025.[24]

The battery reserve model used is described in Figure 7. It first calculates the average time between replacements, expressed in flight hours. This estimate is obtained using the average depth of discharge of batteries, the average number of batteries per aircraft including the spare batteries, the battery capacity, and the yearly utilization of the batteries. Using the average depth of discharge for batteries and typical ageing curves for battery capacity, an estimate of the expected life of the battery is computed. Next, the replacement cost is calculated using the battery capacity and the capacity specific cost (accounting for the entry-into-service date of the electric vehicle). Finally, the battery reserve is computed last by dividing the battery replacement cost by the number of flight hours between replacements.

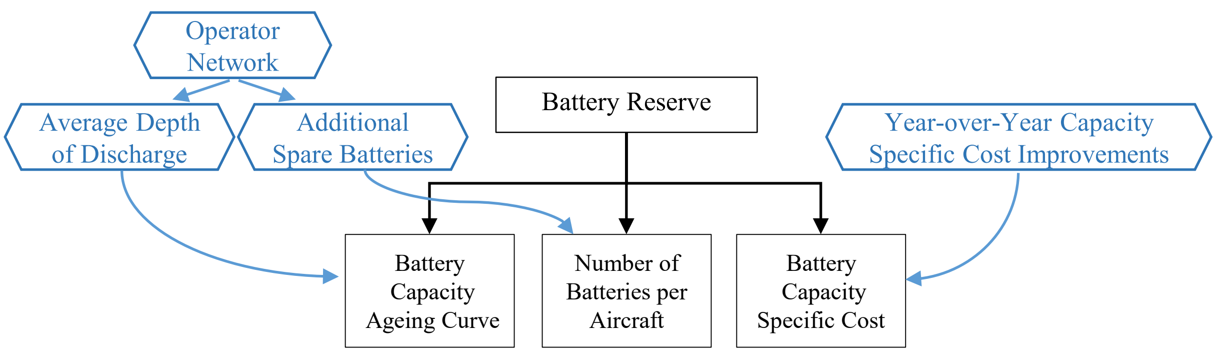

Figure 7. Battery reserve model description

III.E. Ownership Cost Model

The ownership cost refers to the total cost incurred by the operator to own the aircraft over a certain period of time. This includes the financing of the acquisition, the depreciation of the asset over time, as well as the hull insurance. In the proposed model, the aircraft is depreciated over a fifteen-year period and the hull insurance rate is 2% of its market value.

IV. Use Case/ Validation

A use-case is investigated to validate the proposed economic model and to investigate whether rejuvenating the current fleet of a commuter operator is economically sound. The use-case is based on the Part-135 operations of Cape Air, the largest scheduled commuter operator in the United States. Cape Air operates a fleet of 83 Cessna 402, 4 Britten-Norman Islander, and 2 Cessna 208 mostly in the New England area, and to a lesser extent in the Caribbean, Midwest, and Wyoming.

Analyzing the sub-fleet of Cessna 402 reveals that they serve about fifty different routes and perform over four hundred flights per day. Most of these flights are very short with distances ranging from 15 mi (12 nmi) to 322 mi (280 nmi) as shown in Figure 8. About half of the flights are below 90 mi (80 nmi) and about 98% of flights are below 230 mi (200 nmi). Most flights in the network could be flown with a fully-electric mode of operation by one of the DEP concept under review, which makes Cape Air operations a perfect candidate for the introduction of a distributed electric propulsion concept. A comparison of the Cessna 402 currently in operation at Cape Air with one distributed electric propulsion concept is highlighted in Table 1.

Table 1. Characteristics of Cessna 402 and Joby concept

	Cessna 402C	Joby Concept
Capacity [pax]	9	9
Range [mi]	1235	230 (all-electric) / 460 (hybrid)
Speed [kts]	185	316
Fuel tank capacity [gal]	213	67
Battery capacity [kWh]	-	673
Unit cost [M-US$]	1.5	2.9

One significant challenge encountered in this research is the ability to find reliable real-world data to validate the cost models developed. Unlike Part-121 airlines, Part-135 commuter operators are not required to report revenue and cost data, and many commuter operators are not publicly traded companies, meaning that their operating and financial performances are rarely published. Economic data may however be found in the Essential Air Service proposals that these operators submit to the Department of Transportation to get subsidies to operate economically unsustainable routes. EAS proposals of Cape Air submitted during the 2011 to 2016 time period are retrieved and used for validation. In those proposals, the operator provides the expected duration of the service, the expected number of departures, as well as the expected costs and revenues. This data is used to compute the labor, fuel, and maintenance costs for each route in $/mi. These reported numbers are compared to the calculated costs computed using the proposed cost model.

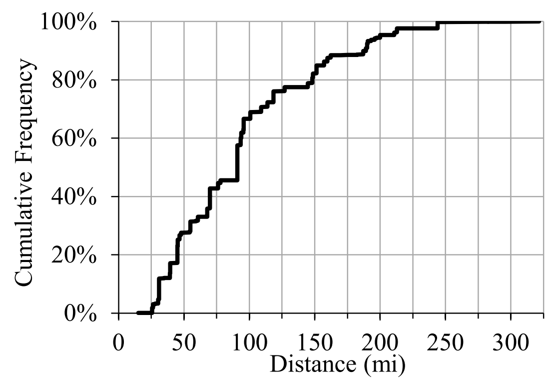

Figure 8. Distance distribution for Cape Air flights

Figure 9 compares the reported and calculated energy costs for fifteen different EAS market applications. Some discrepancies are observed even though the calculated and reported costs are usually within the same range. However, no particular trend in the residuals is observed and thus, there is no reason to reject the proposed model. One difficulty encountered during the validation is that the EAS applications used date back to different years with most likely different, but yet unknown, fuel price scenarios owing to the volatility of fuel prices (EAS proposals do not state the fuel price assumption). The energy cost assumed for the computations uses the price of AVGAS at the airport serviced, averaged over the year prior to the EAS submission.

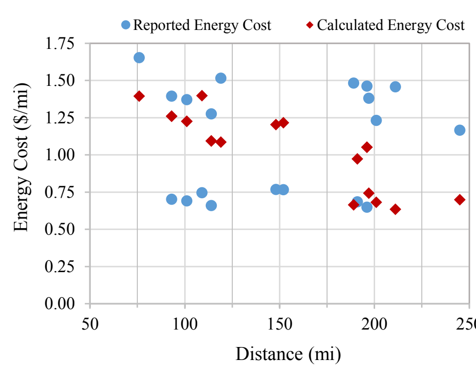

Figure 9. Reported and calculated energy costs for different EAS routes

Figure 10 compares the reported and calculated labor costs across the fifteen EAS markets previously used. Again, some discrepancies are observed but no obvious error pattern is apparent. In this case, most of the issues seem to be related to the data points used for the validation exercise. Indeed, several EAS routes have very similar trip distances and yet exhibit widely different labor costs. One explanation for these discrepancies is that the reported data points used for the validation exercise are from different years ranging from 2011 to 2016. As a result, these data points might reflect the different dynamics observed in the flight-crew labor market (recessions after the 2008 financial crisis followed by a pilot shortage starting in 2014).

Figure 11 compares the reported and calculated maintenance costs across the fifteen EAS markets already used. The maintenance model results match closely the reported costs for a wide range of missions. As a consequence, there is no reason to reject the proposed model. It is worth mentioning that the maintenance cost increases quite steeply as flights get shorter. This is symptomatic of the additional wear and fatigue on the engine and airframe as the number of yearly flight cycles increases.

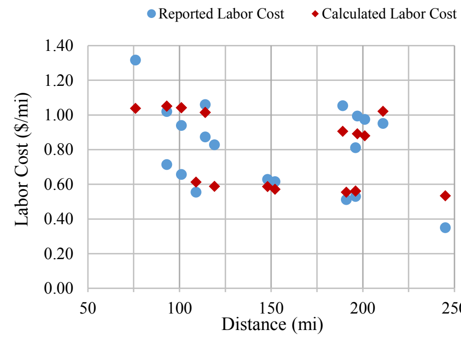

Figure 10. Reported and calculated labor costs for different EAS routes

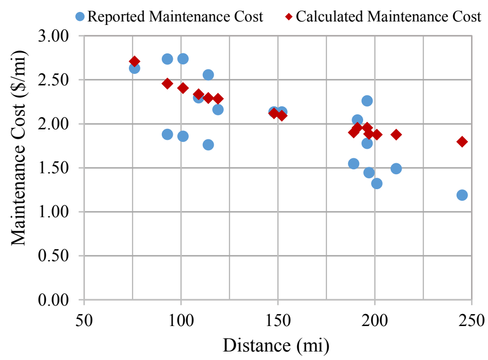

Figure 11. Reported and calculated maintenance costs for different EAS routes

V. Results

Using the methodology discussed in the previous sections, preliminary comparisons between the direct operating costs of the Cessna 402 used by Cape Air and of the proposed DEP aircraft are made. For this analysis, the entry into service for the DEP concept is assumed to be in 2025. This allows for a battery capacity specific cost of 100\$/kWh and a battery life reaching 2,000 charging cycles. The electricity and fuel prices used for this analysis were retrieved in February 2016 for each airport served by Cape Air. Using these assumptions, the direct operating costs associated with each route within the Cape Air network are calculated and then averaged to yield direct operating costs per statute mile. Figure 12 illustrates the breakdown of the direct operating costs for the Cessna 402 and for the DEP concept.

Switching from a conventional commuter aircraft to the envisioned DEP architecture drastically reduces the energy and maintenance components of the total direct operating costs by 70% and 30%, respectively. On the other hand, the ownership cost component increases by 40% owing to the increased acquisition price of the vehicle and the higher insurance premiums. The introduction of the battery reserves for the DEP concept represents 8% of the total direct operating costs. Overall, a 20% reduction in total direct operating costs can be achieved when switching from a conventional aircraft to a DEP concept.

These results are deterministic and assume that everything is known with certainty. Unfortunately, this is not the case for many of the key parameters used and therefore a probabilistic approach recognizing the uncertainty surrounding some of these assumptions is warranted. Monte Carlo simulations are performed by defining distributions for the most uncertain parameters in order to yield a more robust analysis. Uniform distributions are considered and are defined by a lower and an upper bound as described in Table 2. The composite airframe factor is an adjustment factor placed on the function estimating the maintenance man hours required to maintain a composite airframe in airworthy conditions. According to Boeing, a composite airframe requires 35% less maintenance and thus, this factor is varied between 28% and 42% for the simulations. A battery capacity specific cost of 100\$/kWh is assumed to be achievable by 2025. Since the current price is 250\$/kWh and improvements are expected, the battery capacity specific price is varied between

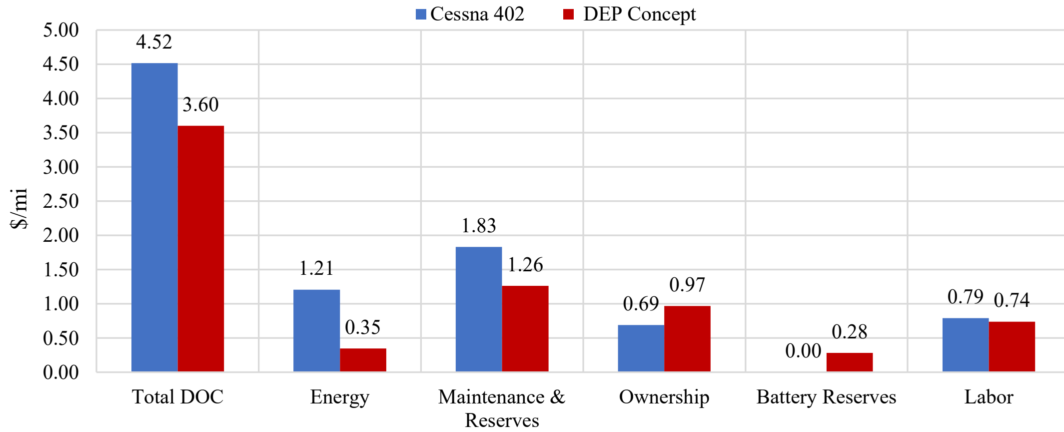

Figure 12. Use case DOC breakdown comparison

100$/kWh and 250$/kWh. Energy prices (fuel or electricity) are retrieved for each and every airport in the network of Cape Air and to account for the high volatility of energy prices, these spot prices are varied by +/-50% of their current value. The engine maintenance cost factor is an adjustment factor used to estimate the maintenance cost of electric motors. Electric motors are expected to yield a 20% reduction in engine maintenance and thus the adjustment factor is varied between 12% and 28% for the simulations.

Table 2. Monte Carlo input parameters and bounds

Category	Initial Model Value	Lower Bound	Upper Bound
Composite Airframe Factor	0.65	0.58	0.72
Battery Capacity Specific Cost	100 $/kWh	100 $/kWh	250 $/kWh
Fuel Price	Varies by airport (as of Feb. 2016)	-50%	+50%
Electricity Price	Varies by airport (as of Feb. 2016)	-50%	+50%
Life of Battery	2,000 cycles	1,000	3,000
Labor Rate	28 $/hour	15 $/hour	45 $/hour
Engine Maintenance Cost Factor	0.8	0.72	0.88

Using these bounds, 10,000 Monte Carlo simulations are performed. The results of these simulations can be synthesized using the cumulative distribution functions of the direct operating costs, the energy costs, and the maintenance costs. The cumulative distribution functions representing the energy and maintenance costs are highlighted Figure 13.

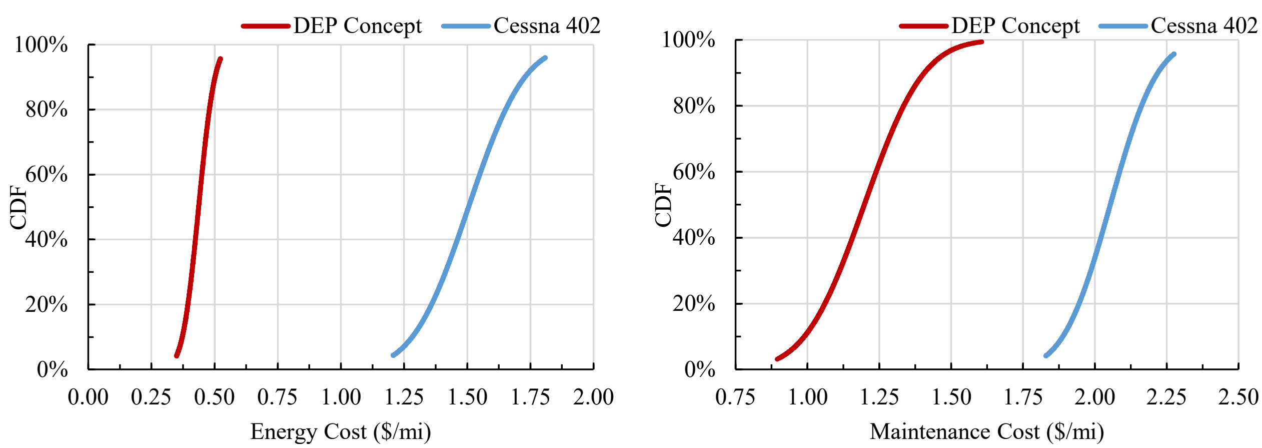

Figure 13. Cumulative distribution function induced by Monte Carlo simulations for energy and maintenance costs

As can be observed in Figure 13, the energy as well as the maintenance costs are significantly reduced. Since the cumulative distribution functions do not overlap, there are always some economic improvements when switching from a conventional aircraft to a DEP concept. The energy cost reduction is due to the significant differences in fuel and electricity prices and the improved efficiency of electric motors. The maintenance cost reduction is mostly due to the reduced maintenance of electric motors and the move to a composite airframe. Figure 14 illustrates the estimated economic impact of switching from a conventional aircraft to an aircraft featuring a distributed electric propulsion. The dashed black curve indicates the 30% reduction target with respect to the total direct operating costs of the Cessna 402.

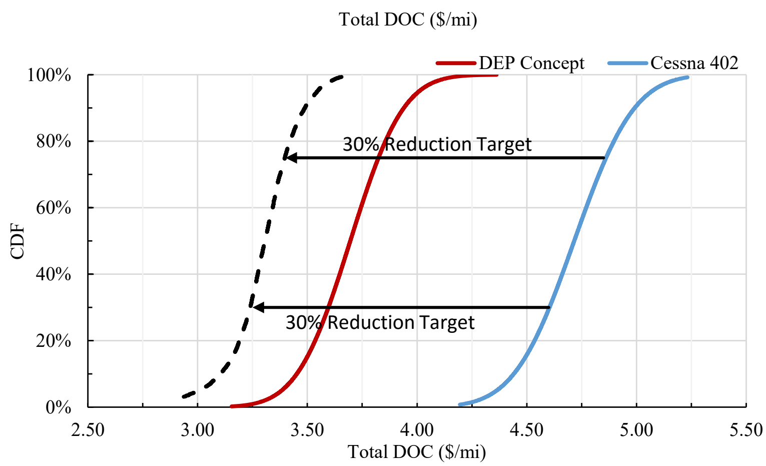

Figure 14. Cumulative distribution function induced by Monte Carlo simulations for direct operating costs

The results obtained so far indicate a drastic reduction in energy and maintenance costs for every case investigated in the Monte Carlo simulations. The resulting direct operating costs are also significantly reduced, however, the target reduction of 30% of the direct operating costs seems unlikely to be met. As a result, it is necessary to investigate ways to further improve the economics of the distributed electric propulsion concept. Due to the uncertainty regarding energy prices and battery technology, gauging the sensitivity of the direct operating costs to these two factors may prove insightful. A sensitivity study helps determine viable operating scenarios i.e. what combination of electricity prices and battery technology achievements are needed to reach the target reduction. In order to highlight these sensitivities, the developed framework is used along with sweeps for each of these two design variables. Electricity prices are varied between 0.04$/kWh and 0.20$/kWh, while fuel prices are varied between 1.50$/gal and 10$/gal. For each electricity price and fuel price combination, the difference in direct operating costs between the two aircraft is calculated and a contour plot is generated (contours with negative labels indicate percentage reduction in operating costs) in Figure 15a. It should be mentioned that the marker on Figure 15a represents the average fuel price and average electricity price observed across all airports in the network considered.

As may be observed in Figure 15, the DEP concept is viable for a variety of energy prices. The 30% reduction target can be reached when fuel prices exceed 8.00$/gal for current electricity price assumptions. Should electricity prices go as low as 0.04$/kWh in the future, this 30% reduction target can be reached with fuel prices as low as about 7.50$/gal. These lower electricity rates can potentially be achieved through optimized charging schedules or energy storage. However, it seems unlikely that the energy savings alone will yield enough benefits to reach the 30% reduction target in direct operating costs. The sensitivity of direct operating costs to battery technology is another important trade study that can be investigated. For this trade study, the battery life is varied between 500 and 3,500 cycles while the battery capacity specific cost is varied between 50$/kWh and 300$/kWh. The results are presented in Figure 15b. Although current battery technologies do not yield enough improvements, the battery technologies that will be available in 2025 for the targeted entry into service of the DEP concept seem to make significant strides towards the targeted 30% reduction in total DOC. A reduction in battery capacity specific cost coupled with an increase in battery life increases the viability of the thin-haul concept. It is important to point out that battery research is very active and significant progress is expected over the next decade. Careful charging schedules and power usage could also extend battery life and reduce the costs associated with battery reserves. Given

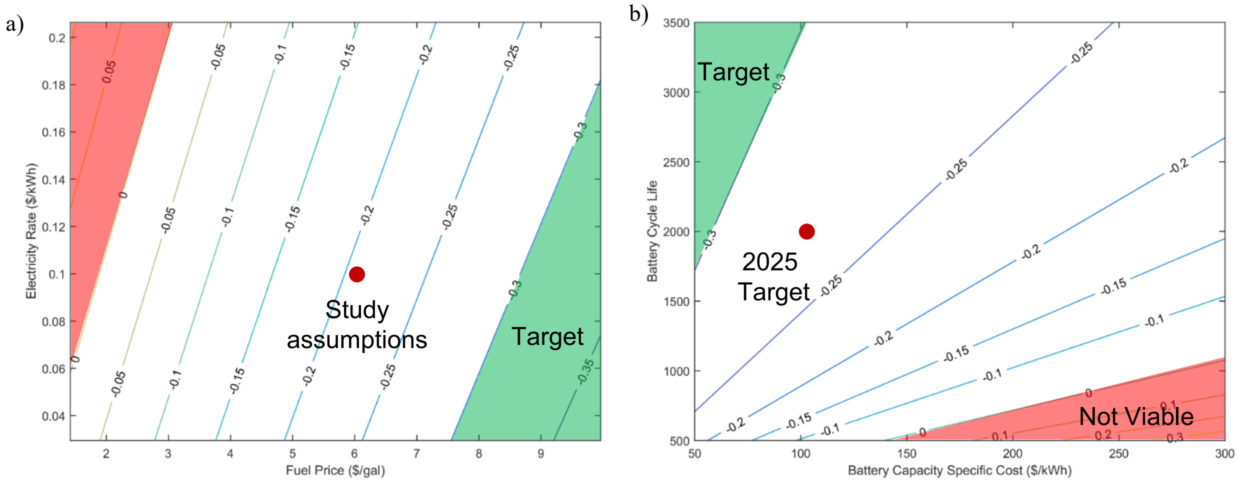

Figure 15. Energy price (a) and battery technology (b) trade studies

these two trade studies, it becomes apparent that the targeted reduction of 30% in the direct operating costs can only be reached via the convergence of many technologies as each technology cannot bring enough saving on its own. In any case, the estimated savings obtained in this study are still dramatic and a 20% reduction of the direct operating costs seems readily achievable.

VI. Conclusion

The presented research investigates the use of distributed electric propulsion as an enabler for the revitalization of thin-haul aviation following several decades of decline or stagnant growth of commuter operations in the United States. The use of distributed electric propulsion to renew the current ageing fleet of small commuter aircraft also provides a unique opportunity to fundamentally reshape the public perception of small commuters by marketing them as energy efficient advanced vehicles offering smooth and comfortable rides. To determine whether these new concepts are suitable for thin-haul aviation missions, the research starts with a review of a typical commuter operation and then investigates the economic impact of introducing a new electric vehicle to replace the existing fleet of twin piston aircraft. The figure of merit retained for this analysis is the direct operating cost and the viability of the vehicle is assessed by measuring the reduction in direct operating cost experienced by operators. The analyses performed in this research indicate a staggering 20% reduction in expected operating costs with improvements mostly driven by lower energy expenditures and reduced maintenance costs. These results are assuming a one-to-one replacement of the existing fleet and no change to the operational statistics (yearly utilization, average turn-around-time). Besides the operating cost improvements, a side study of this research indicates that the life-cycle emission of green-house gases (carbon dioxide, methane, and nitrous oxide) would be reduced by up to 75% when taking into account the emissions from the vehicle during operations as well as the emissions from the production and transportation of energy (fuel and electricity) to the airports. This estimate accounts for the energy mixes (nuclear, coal, hydroelectric) used by utility providers to produce electricity at the various locations serviced by the commuter operator considered in this study. More detailed analyses are however warranted in order to overcome some of the limitations of the current study. In particular, research is currently being performed to analyze the detailed schedule of three different thin-haul operators in order to:

- Design energy-replenishment strategies at each airport serviced during the daily operation of each tail number in the fleet that do not impact the flight schedules (already optimized to meet demand and for revenue-management purposes). Indeed, it is not certain that current tight turnarounds at airports provide sufficient time to replenish batteries for subsequent flights. Therefore, the use of super-chargers, range extenders, and battery swap strategies are investigated.
- Get a more accurate estimate of the electricity rate that commuter operators would be charged for the replenishment of batteries. Indeed, both a detailed analysis of the flight schedule and the selection of

an energy-replenishment strategy are necessary to yield requirements regarding the number of charging stations at each airport in the network. In turn, this impacts the energy demand ($/kWh) and the peak power demand /kW) that are the major drivers of the electricity rate..

- Assess if yearly utilization (flight hours) could be increased owing to reduced maintenance requirements and reduced spare aircraft requirements. This could mitigate the increase in ownership costs experienced when transitioning from a fleet of fully-amortized aircraft to a fleet of brand new aircraft.

In addition, the current convergence of technologies may yield further improvements to the economics of these novel concepts. Indeed, these new concepts seem like the ideal platform to benefit from many technologies developed for the more electric aircraft, and in particular those technologies related to simplified vehicle operations and increased autonomy. Simplified vehicle operations have the potential to reduce crew training expenditures and to reduce labor costs by facilitating the transition to single-pilot operations, while improving the safety of commuter operations.

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